Ranking Interventions to Improve Inner-City Housing Indoor Air Quality

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ABSTRACT
The U.S. Department of Housing and Urban Development (HUD) has identified a need to improve urban housing conditions to protect children's health through its Healthy Homes Initiative (HHI). One critical area within this program is to address a wide range of indoor air quality (IAQ) concerns (*e.g.*, inadequate ventilation, combustion by-products, *etc*.) with an effective intervention strategy. To evaluate the impact of different interventions on indoor contaminant concentrations and occupant exposures, a simulation study was conducted with the multizone airflow and contaminant dispersal model CONTAM. This study modeled the exposures of a family of five to concentrations of carbon dioxide, carbon monoxide, water vapor, nitrogen dioxide, 0.3 μm to 10 μm particles, radon, and volatile organic compounds in a three-story townhouse. The model included leakage characteristics of the house, ambient weather conditions, indoor environmental conditions, outdoor and indoor sources of the contaminants as well as adsorption and deposition loss mechanisms. With these inputs, CONTAM was used to predict ventilation rates, contaminant concentrations and occupant exposures for a baseline case and combinations of four different interventions based on a factorial simulation design. The interventions included tightening the envelope, adding mechanical ventilation, using kitchen and bathroom exhaust fans, and installing a higher efficiency air filter. A statistical analysis ranked the interventions individually and in combination for each study contaminant. Overall, a combination of mechanical ventilation, local exhaust, and an improved air filter was most effective for reducing the largest number of contaminants in the study. Except for contaminants originating primarily outdoors, tightening the envelope resulted in higher indoor concentrations, even when done in combination with mechanical ventilation. Although only a small number of interventions were investigated for this demonstration project, the statistical ranking method could be applied to future intervention studies to consider other strategies, costs, contaminant toxicity, etc.

INTRODUCTION
Several air contaminants measured indoors have been shown to have negative impacts on human health.[1-4] Residential indoor air pollutants of concern include: combustion byproducts, volatile organic compounds, radon, and bioaerosols.[5-7] Many of these contaminants are often measured at higher concentrations in lower income urban housing.[8-11] Although these residences are typically in the greatest need of remediation, they are the least likely to be fixed. As such, the U.S. Department of Housing and Urban Development (HUD) has made it a priority to identify wide reaching intervention strategies that can be feasibly implemented to improve the indoor air quality (IAQ) in lower income homes. As part of this effort, HUD's Healthy Homes Initiative

(HHI) is funding several demonstration projects to implement interventions that correct IAQ problems found in lower income urban homes. Due to the costs of fieldwork, however, the demonstration projects are only able to implement a limited number of interventions in a small number of homes. A more feasible way to prioritize the hazards and identify the farthest-reaching intervention strategies is through modeling. A modeling approach allows the evaluation of many potential interventions under a wider variety of conditions to help provide a knowledge base for recommending the most effective strategies. Such modeling can also be used to evaluate the interventions for possible unintended negative impacts. Thus, model results have the potential to provide tremendous insight toward the improvement of IAQ in urban housing with multiple deficiencies.

The National Institute of Standards and Technology (NIST) conducted a study for HUD to simulate the impact of several intervention strategies. For this study, NIST developed a multizone airflow and IAQ model of an urban house using the CONTAM IAQ simulation program. The simulations incorporated occupancy schedules for a family of five, weather conditions for all seasons in three U.S. cities, twelve contaminants with multiple indoor sources and outdoor concentrations, and contaminant sinks. The model was used to evaluate the individual impact of eight different interventions on contaminant concentration and occupant exposure. In addition to these 108 simulations to evaluate individual interventions, 16 more simulations were conducted to look at the impacts of combinations of interventions, which are the focus of this paper. When there is a single specific contaminant of concern, it is rather straightforward to determine the most effective intervention. However, typically there are several indoor air contaminants of concern that cannot all be addressed with a single intervention. As a result, combinations of interventions may be needed to address overall indoor air quality. To examine this issue, a subset of interventions (mechanical ventilation, exhaust fans, improved filter, and envelope tightening) was identified for use in a factorial simulation design to determine the most effective combination of interventions for all contaminants based on occupant exposure. This paper presents the statistical methodology used to rank combinations of interventions and the results from this portion of the project. Results from the entire project will soon be available in a NIST report.[12]

SIMULATION METHODS

The simulation program used in this study is CONTAM, a multizone IAQ and ventilation model developed in the Building and Fire Research Laboratory (BFRL) at NIST.[13] The multizone approach is implemented by constructing a building model as a network of elements describing the flow paths (HVAC ducts, doors, windows, cracks, etc.) between the zones of a building. The network nodes represent the zones, which are modeled at a uniform pressure, temperature, and pollutant concentration. After calculating the airflow between zones and the outdoors, zone pollutant concentrations are calculated by applying mass balance equations to the zones, which may contain pollutant sources and/or sinks.

Baseline Building Model

A well-studied CONTAM model of a townhouse was used as a baseline building for this project.[14] Most recently, the townhouse model was validated for its ability to predict air change rates and SF_6 concentrations based on measured data. Although the original model was based on a house not considered typical of lower income urban housing, it was modified to be more representative of this housing type. The model townhouse is a three-story, three bedroom, three bathroom end-unit townhouse with a floor area of approximately 35 m^2 per level and an approximate living space volume of 250 m^3. The unfinished basement is three-quarters underground with no outside access doors. The basement contains a gas furnace, gas hot water heater and dryer, all vented to the outside. The second level consists of a kitchen, living room, and bathroom. There is a sliding glass balcony door and fireplace in the living room. The third level includes three bedrooms, two bathrooms, and several closets. The fourth level is an attic, with a volume of 50 m^3. A floor plan of the house as entered into CONTAM is shown in Figure 1.

To characterize the airflow between zones and the outdoors, CONTAM uses different types of flow elements. Most of the model flow elements for this project use leakage area data from the literature for different types of openings (e.g., wall-to-wall joints, electrical outlets, window frames, *etc*.).[15] Other flow element types used in this model include orifice area data for the attic vents and two-way openings for the open doorways between zones. Leakage area elements were also used for airflow paths between zones at interior walls, ceilings and floors.

A variable wind pressure coefficient was applied to the exterior envelope leakage elements. Wind pressure coefficients characterize the relationship between wind and surface pressures and depend on the wind direction, the building shape, the position on the building surface, and the presence of shielding near the building. Equations provided in the ASHRAE Fundamentals Handbook were used to construct a wind pressure profile for the model house.[15]

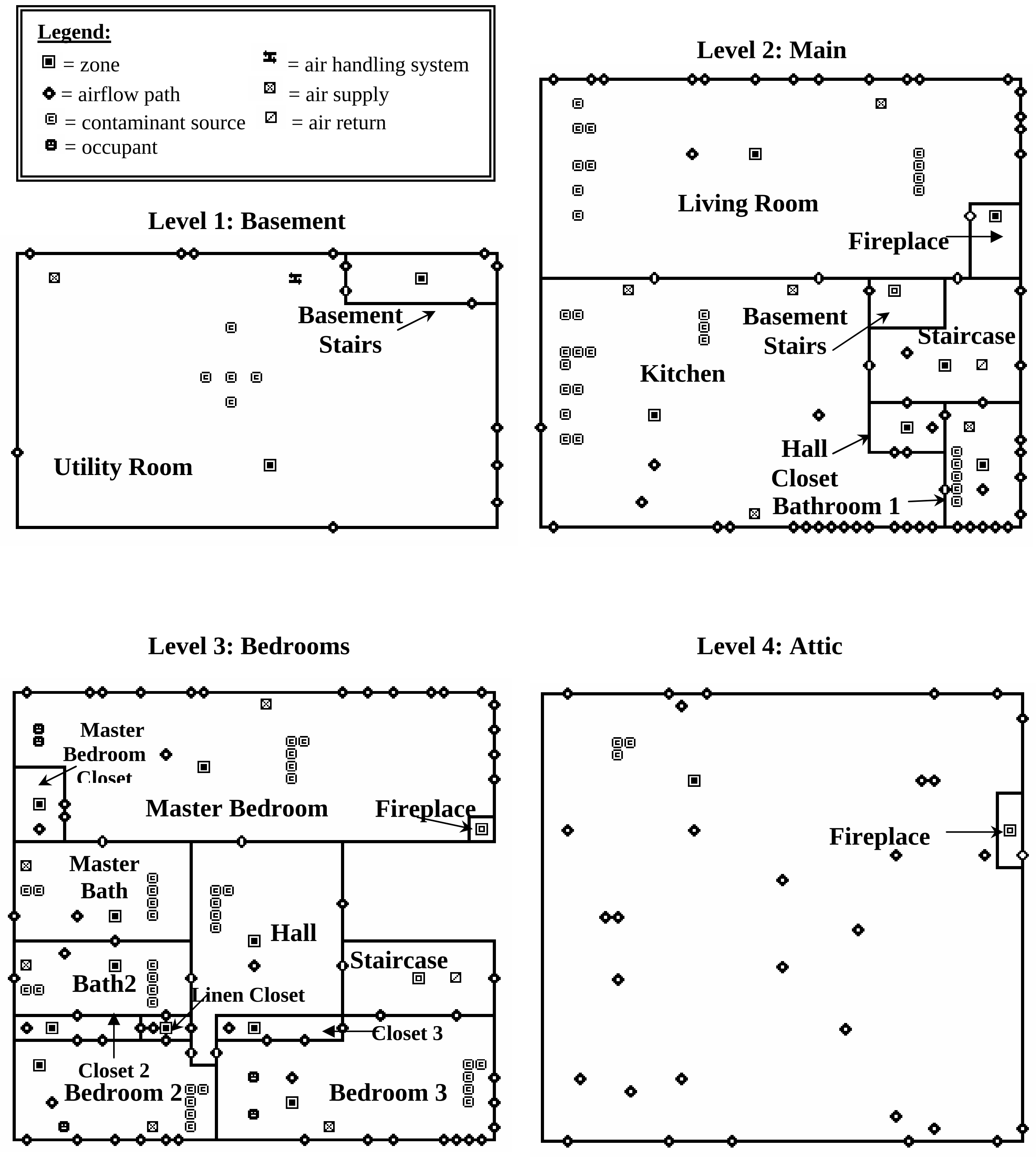
A simple recirculating air handling system (AHS) was added to the model and operated on a schedule of the first ten minutes of each hour. The system ductwork does not enter the attic, resulting in insignificant duct leakage to the outside. The system was modeled as operating with a total volumetric airflow of 0.35 m^3/s.

For the factorial analysis presented in this paper, the house was modeled using representative fall weather conditions in Boston, MA. Transient simulations were performed using TMY2 weather data.[16] For a representative fall week, the average outdoor temperature was 7 °C and the average wind speed was 5.6 m/s. The indoor temperature was 20 °C for all zones.

Occupants

To account for occupant-generated contaminants and to determine the exposure of building occupants to indoor contaminants, a family of five was assumed to occupy the townhouse. The occupants of the house included an adult male, adult female, and three children of ages 4, 10, and 13 years. A weekend (Saturday and Sunday) and weekday (Monday – Friday) schedule was fabricated for each family member that specifies the time spent in each room of the house, as well as time outside of the house. The father spent 69 % of the study week in the house, whereas the mother and four-year old spent 92 % of their time in the house. The other two children were in the house an average of 75 % of the study week. During the time spent outside of the house, the occupant exposure was assumed to be zero. Based on these schedules CONTAM accounts for the contaminant generated by each individual in the room where they are located at a given time and keeps track of the contaminant concentrations to which they are exposed. CONTAM then calculates the mean concentration over a given period of time as a measure of exposure.

Figure 1: Floor Plan of House in CONTAM



Contaminants and Sources

The contaminants that were considered for the factorial simulations include carbon dioxide (CO_2), carbon monoxide (CO), nitrogen dioxide (NO_2), airborne particles (in 5 sizes ranging from 0.3 μm to 10 μm), volatile organic compounds (VOCs) and radon (Rn). The sources of these contaminants were not intended to be comprehensive, but rather representative of some typical residential occupancies and to provide insight into each of the individual contaminants. It should be noted that water vapor was included as a contaminant in the overall project where room concentrations were reported, but it was not considered an important contaminant here in terms of occupant exposure.

Carbon Dioxide

In general, concentrations of carbon dioxide (CO_2) do not reach harmful levels indoors, however these concentrations have often been used as an indicator of ventilation. The only indoor source of CO_2 considered for this study was the respiration of the occupants. The generation rate of CO_2 from a person is a function of body size and physical activity. Table 1 shows the occupant CO_2 generation rates used for awake and sleeping time periods based on ASHRAE Fundamentals Handbook.[15] The locations of these CO_2 sources depend on the occupant schedules discussed above. Another important source of CO_2 was the outdoor air which was assumed to have a constant concentration of 630 mg/m^3 (all outdoor concentrations are presented in a later section in Table 6).

Table 1. Occupant generation rates of CO_2.

Occupant	**Weight (kg)**	**CO_2 generation rate – awake (mg/s)**	**CO_2 generation rate – sleeping (mg/s)**
Adult Male	81	11	6.6
Adult Female	67	9.8	6.2
Child #1 (13 years old)	50	8.6	5.2
Child #2 (10 years old)	36	6.8	4.1
Child #3 (4 years old)	17	3.8	2.3

Carbon Monoxide and Nitrogen Dioxide

The indoor source of CO and NO_2 was a gas stove. Table 2 shows the generation rates and schedules for the gas stove, which are based on values in the literature.[17]

Table 2. Sources of CO and NO_2.

Source	CO generation rate (mg/s)	NO_2 generation rate (mg/s)	Location	Weekday schedule	Weekend schedule
Gas stove – breakfast	0.21	0.028	Kitchen	6:30 a.m. – 7:00 a.m.	9:30 a.m. – 10:00 a.m.
Gas stove - lunch	0.42	0.056	Kitchen	12:00 p.m. – 12:30 p.m.	12:00 p.m. – 12:30 p.m.
Gas stove - dinner	0.42	0.056	Kitchen	5:00 p.m. – 5:30 p.m.	5:00 p.m. – 5:30 p.m.
Gas stove – dinner	0.83	0.11	Kitchen	5:30 p.m. – 6:00 p.m.	5:30 p.m. – 6:00 p.m.

Airborne Particles

Airborne particles of many different sizes and composition are generated by combustion and mechanical processes. Although these different properties of airborne particles determine their health impacts, this study only addressed particle size as it impacts generation rates and removal. The model included 5 particle size ranges (P1: 0.3 μm to 0.5 μm; P2: 0.5 μm to 1.0 μm; P3: 1.0 μm to 2.5 μm; P4: 2.5 μm to 5.0 μm; P5: 5.0 μm to 10 μm), which correspond to size ranges commonly measured in the field.[18-20] Indoor particle sources included cooking (for generation of smaller particles) and changing of kitty litter twice a week (for generation of larger particles). As with the other contaminants, many other potential sources of particles may exist in any given residence. These sources were chosen as examples based on the availability of source strength data. The source strengths for these events were based on measurements in previous studies and are summarized in Tables 3 and 4.[19-20]

Table 3. Particle generation rates and schedules for cooking.

Source	Particle Generation Rate (number per h)			Location	Weekday Schedule	Weekend Schedule
	0.3-0.5 μm	0.5-1.0 μm	1.0-2.5 μm			
Cooking – Breakfast	6.4×10^{10}	1.6×10^{10}	8.0×10^{9}	Kitchen	6:30 a.m. – 6:40 a.m.	9:30 a.m. – 9:40 a.m.
Cooking – Lunch	4.0×10^{10}	1.0×10^{10}	5.0×10^{9}	Kitchen	12:00 p.m. – 12:10 p.m.	12:00 p.m. – 12:10 p.m.
Cooking – Dinner	8.0×10^{10}	2.0×10^{10}	1.0×10^{9}	Kitchen	5:00 p.m. – 5:10 p.m.	5:00 p.m. – 5:10 p.m.

Table 4. Particle generation rates and schedules for changing kitty litter.

Source	Particle Burst Amount (number of particles)	Location	Weekday Schedule	Weekend Schedule
Kitty Litter: 0.5 to 1.0 μm	5.6×10^{8}	Living Room	Wednesday @ 9:20 a.m.	Saturday @ 9:20 a.m.
Kitty Litter: 1.0 to 2.5 μm	5.0×10^{8}			
Kitty Litter: 2.5 to 5.0 μm	6.8×10^{8}			
Kitty Litter: 5.0 to 10 μm	7.9×10^{8}			

Radon

A pressure dependent radon source described in an earlier NIST report was included in the basement zone of the model (see Equation 1).[21]

Equation 1. Source model for radon.

$$S = G\Delta P^{n}$$

where:

S = contaminant source strength ($Bq/s \cdot m^2$)
G = generation rate coefficient ($Bq/s \cdot m^2 \cdot Pa$)
ΔP = pressure difference (Pa)

n = pressure exponent (-)

With little information available in the literature for model inputs, the value of G was determined based on it yielding reasonable concentrations in the house.[22] As with all contaminants, exact values were not critical, since analysis for this project is based on relative concentrations. Based on these trial simulations a generation rate of 0.004 $Bq/s \cdot m^2 \cdot Pa$ and a pressure exponent of 1 were chosen.

Volatile Organic Compounds

Volatile organic compounds (VOCs) include a broad class of chemicals with wide variations in physical and chemical properties, health impacts, and sources. The study includes two nonspecific VOCs as surrogates for two general classes of sources. The first VOC was generated in each room of the house with a generation rate proportional to the floor area. A continuous generation rate of 0.2 $mg/h \cdot m^2$ was used, based on an average of approximately fifty published flooring emission rates for toluene.[23] The second VOC was generated by a burst source in different rooms of the house. Based on an emission rate for floor cleaning, a mass of 0.08 g was used for the burst.[24] The release location and schedule of the burst VOC source is shown in Table 5.

Table 5. Location and schedule for burst VOC sources.

Location	Day of Week	Time
Kitchen	Monday - Friday	7:30 a.m.
	Saturday and Sunday	10:30 a.m.
Bathroom #1	Saturday	11:00 a.m.
Living Room	Saturday	11:20 a.m.
Master Bedroom	Saturday	11:30 a.m.
Master Bathroom	Saturday	11:40 a.m.
Hall	Saturday	3:40 p.m.
Bedroom #2	Saturday	3:50 p.m.
Bedroom #3	Saturday	4:00 p.m.
Bathroom #2	Saturday	4:40 p.m.

Outdoor Concentrations

Outdoor concentrations of CO, NO_2, CO_2, and VOCs were based on those used in earlier NIST studies and are presented in Table 6.[17,25] Outdoor particle concentrations were based on average concentrations measured outside a research townhouse in Reston, VA.[18] It should be noted that Reston is considered a suburban location where outdoor pollutant levels may not be as high as an urban location. Nonetheless, a constant value for each particle size range was used.

Table 6. Outdoor concentrations of CO, NO_2, CO_2, VOCs, and particles.

Time / Contaminant	12:00 a.m. – 7:00 a.m.	7:00 a.m. – 9:00 a.m.	9:00 a.m. – 5:00 p.m.	5:00 p.m. – 7:00 p.m.	7:00 p.m. – 12:00 a.m.
CO (mg/m^3)	1.1	2.3	1.7	3.4	1.7
NO_2 (mg/m^3)	0.038	0.075	0.038	0.075	0.038
CO_2 (mg/m^3)	630	630	630	630	630
VOC (mg/m^3)	0.10	0.10	0.10	0.10	0.10
P1: 0.3 to 0.5 μm ($\#/cm^3$)	64	64	64	64	64
P2: 0.5 to 1.0 μm ($\#/cm^3$)	3.7	3.7	3.7	3.7	3.7
P3: 1.0 to 2.5 μm ($\#/cm^3$)	0.39	0.39	0.39	0.39	0.39
P4: 2.5 to 5.0 μm ($\#/cm^3$)	0.11	0.11	0.11	0.11	0.11
P5: 5.0 to 10 μm ($\#/cm^3$)	0.020	0.020	0.020	0.020	0.020

Removal Mechanisms

Contaminant Sinks

The loss of contaminants due to adsorption, deposition and decay were also included in the model. Reversible sink effects for VOCs were modeled with sink elements based on the boundary layer diffusion controlled (BLDC) model, which is described in detail elsewhere.[26] The parameters required for this sink model are the film mass transfer coefficient, the adsorbent mass and the partition coefficient. Sink values for VOCs are given in Table 7. It was assumed that these values apply to all living areas of the house, except for closets and stairways.

Table 7. Boundary layer diffusion controlled model parameters.

Parameter	VOC values
Film Transfer Coefficient	0.08 m/h
Film Density	1.2 kg/m^3
Surface Mass	550 kg
Partition Coefficient	5

Nitrogen dioxide decay and particle deposition were modeled as single-reactant first order reactions with a single, constant value in all rooms of the houses. The kinetic rate coefficient used for NO_2 decay was 0.86 h^{-1} and is based on the average of measurements in a contemporary research house.[27] Particle deposition rates were measured in a research townhouse and reported elsewhere.[19] A summary of the deposition rates is given in Table 8.

Table 8. Deposition rates for NO_2 and particles.

Contaminant	Deposition Rate (h^{-1})
NO_2	0.86
P1: 0.3 μm to 0.5 μm	0.30
P2: 0.5 μm to 1.0 μm	0.42
P3: 1.0 μm to 2.5 μm	0.78
P4: 2.5 μm to 5.0 μm	1.4
P5: 5.0 μm to 10 μm	2.7

The half-life of Radon-222 is 3.8 d, which corresponds to a decay rate of 0.0076 h^{-1}.

Air Cleaning
Particles were also removed in the baseline cases with a central HAC system by a typical furnace filter. Removal rates were based on experimental results of a previous NIST study.[28] The specific removal rates for each particle size were as follows: 7.5 % for 0.3 μm to 0.5 μm, 14 % for 0.5 μm to 1.0 μm, 20 % for 1.0 μm to 2.5 μm, 20 % for 2.5 μm to 5.0 μm, and 20 % for 5.0 μm to 10 μm. These removal values were based on results from an experimental study[27] rather than a minimum reporting efficiency value (MERV) curve.[29] Note that these removal rates also account for losses through deposition to the ductwork.

Scenarios/Interventions
For this portion of the project, a subset of the housing repairs/interventions was selected that is largely based on recommendations of ASHRAE 62.2-2004.[30] The interventions/scenarios were as follows:

Replace typical furnace filter with enhanced particle air cleaner
For the baseline simulations, a typical furnace filter was used in the HAC system. For the intervention, the furnace filter was replaced with a higher efficiency mechanical air cleaner. The particle removal efficiencies for the improved air cleaner were based on a previous study[28] and are given in Table 9. These filters were manufactured before the development of MERV curves.[29]

Table 9. Comparison of removal efficiencies of typical furnace filter and intervention mechanical air cleaner.

Particle Size (μm)	Typical Furnace Filter Removal Efficiency (%)	Enhanced Mechanical Air Cleaner Removal Efficiency (%)
0.3 – 0.5	7.5	36
0.5 – 1.0	14	49
1.0 – 2.5	20	62
2.5 – 5.0	20	62
5.0 - 10	20	62

Inclusion of kitchen and bathroom exhaust fans
The baseline cases did not include local exhaust fans. This intervention, involved the inclusion of intermittent kitchen and bathroom exhaust fans that meet the requirements of ASHRAE Standard 62.2.[30] The kitchen fan has airflow of 47 L/s and was operated during cooking events (see Table 3). The bathroom exhaust fans had airflows of 24 L/s and were operated during showers. Bathroom exhaust fans were added to remove water vapor, which was included as a contaminant in the project, but is not considered in this paper.

Installation and operation of a mechanical ventilation system that meets the requirements of ASHRAE Standard 62.2-2004
ASHRAE Standard 62.2 requires the installation of a mechanical exhaust system and/or supply system to provide outdoor air to a dwelling.[30] The amount of outdoor ventilation air is based on the house's floor area and number of bedrooms. The continuous outdoor air requirement may be adjusted to an intermittent value based on the ventilation effectiveness and fractional time on.

There are also some special stipulations for extreme climates. For the fall season in Boston, an exhaust fan continuously operating at 24 L/s was installed in the master bathroom to meet the mechanical ventilation requirement.

Tighten the exterior envelope

A common suggestion to reduce residential energy consumption is to tighten a house's exterior envelope. Tightening a building results in lower infiltration rates, which in turn reduces the number of outdoor contaminants entering the building, but also increases the indoor concentration of contaminants generated inside the building. To model this intervention, all exterior envelope leakage area elements were reduced by 40 % relative to the baseline case.

To evaluate different combinations of these four interventions, a full factorial simulation design was used.[31] This methodology tests the significance of individual interventions as well as ranks combinations of interventions. A full factorial design also has the advantage of being able to detect when variables do not act additively on a specific response. The factorial design for the four interventions is shown in Table 10. Simulation number one is considered the baseline case with simulations 2 – 16 representing all possible combinations of interventions. The impact of each combination of interventions was assessed based on the sum of individual exposures of the five occupants living in the house.

Table 10. Factorial design for four intervention combinations.

Simulation Number	Tightened Envelope	Exhaust Fans	Mechanical Ventilation	Upgraded Filter
1	no	no	no	no
2	yes	no	no	no
3	no	yes	no	no
4	yes	yes	no	no
5	no	no	yes	no
6	yes	no	yes	no
7	no	yes	yes	no
8	yes	yes	yes	no
9	no	no	no	yes
10	yes	no	no	yes
11	no	yes	no	yes
12	yes	yes	no	yes
13	no	no	yes	yes
14	yes	no	yes	yes
15	no	yes	yes	yes
16	yes	yes	yes	yes

SIMULATION RESULTS

A total of 16 simulations were completed to identify the most effective combination of four interventions to reduce a family's exposure to eleven indoor air contaminants. The impact on family exposure (sum of all 5 occupant's individual exposures) for each contaminant is shown in Table 11. A negative value in Table 11 represents an overall reduction in family exposure, and a positive value represents an increase in exposure. The largest reduction in exposure for each contaminant is highlighted with a shaded cell.

Individually, each intervention strategy had advantages and disadvantages. For example, air cleaning alone (Intervention Simulation #9 in Table 11) is a positive intervention that reduces particles originating indoors and outdoors with no negative impact on other contaminant concentrations. Most homeowners, however, only have access to air cleaners that remove particles, limiting the scope of the intervention. While an effective intervention for removing particles, an in-duct air filter as studied only works when the HAC system is operating. For this project, the HAC system was operated the first ten minutes of every hour. This intervention would have been most effective at reducing exposure to particles if the HAC system had been operated continuously. However, it is important to consider the balance between costs of operating the HAC system and removal of particles.

ASHRAE 62.2-2004 recommends using an air filter with a MERV rating of 6 with supply mechanical ventilation.[30] The primary purpose of this filter is to keep the equipment and coils clean. However, as will be discussed below, this recommendation also helps to reduce the negative impact of mechanical ventilation, since it will reduce concentrations of contaminants originating outdoors.

The exhaust fan was the most effective intervention strategy for reducing peak concentrations associated with cooking. This reduction in concentration during source events had a significant impact on the occupants' exposure to CO, NO_2, P2, and P3. Of the four interventions evaluated here, the exhaust fan was the single most effective intervention for exposure to CO and NO_2 (see Intervention Simulation #3 in Table 11).

Exhaust fans had a broader positive impact on contaminants other than CO, NO_2, P2, and P3. During operation, the exhaust fan increased the house's negative pressure causing more outdoor air to enter through leakage paths. As a result, the concentrations of contaminants from continuous sources in other parts of the house (e.g., VOC1 and radon) were also diluted by the increased air change rate. The downside of this intervention strategy was the increase in concentrations of contaminants originating outdoors. This negative impact was significant for P4 and P5. The benefits of using an exhaust fan during source events, however, far outweighed the negative impacts. In fact, project results showed that using the exhaust fan during more source events (e.g., cleaning in kitchen or bathroom) would have reduced concentrations and exposures even more.

If there is no exhaust fan installed or if the existing fan is a recirculating kitchen hood, there will be an installation cost associated with this intervention. However, in some cases, it is a matter of educating the occupants to turn on the fan during source events. There is also an electricity cost associated with operating the exhaust fan on a regular basis that should also be considered. As shown by the project results, there is a potential negative impact from continuously operating an exhaust fan in areas with higher concentrations of contaminants outdoors.

Table 11. Change in family exposure for factorial simulation design.

Int #	Tight	Exh. Fan	Mech. Vent.	Filter	CO (%)	CO_2 (%)	NO_2 (%)	P1 (%)	P2 (%)	P3 (%)	P4 (%)	P5 (%)	Rn (%)	VOC1 (%)	VOC2 (%)
1	no	no	no	no	0	0	0	0	0	0	0	0	0	0	0
2	yes	no	no	no	83	38	53	-20	5.5	-18	-25	12	180	88	83
3	no	yes	no	no	-19	-1.5	-33	-4.5	-16	-8.2	2.3	1.4	-8.7	-1.5	-0.7
4	yes	yes	no	no	4.4	30	-27	-32	-34	-36	-21	13	130	73	73
5	no	no	yes	no	-10	-7.4	-12	4.5	0	6.6	12	3.6	-27	-9.4	-9.8
6	yes	no	yes	no	24	5.8	24	-6.4	3.4	-4.2	-2.8	18	34	24	18
7	no	yes	yes	no	-22	-8.3	-36	1.0	-12	0.2	14	4.5	-32	-10	-10
8	yes	yes	yes	no	-12	3.0	-29	-14	-22	-17	0.4	19	15	19	14
9	no	no	no	yes	0	0	0	-17	-18	-16	-12	-5.9	0	0	0
10	yes	no	no	yes	83	38	53	-42	-21	-35	-35	5.2	180	88	83
11	no	yes	no	yes	-19	-1.5	-33	-21	-31	-23	-9.7	-4.8	-8.7	-1.5	-0.7
12	yes	yes	no	yes	4.4	30	-27	-50	-50	-49	-31	7.1	130	73	73
13	no	no	yes	yes	-10	-7.4	-12	-11	-16	-9.1	-0.7	-2.6	-27	-9.4	-9.8
14	yes	no	yes	yes	24	5.8	24	-26	-18	-21.4	-15	10	34	24	18
15	no	yes	yes	yes	-22	-8.3	-36	-14	-26	-14	1.2	-1.6	-32	-10	-10
16	yes	yes	yes	yes	-12	3.0	-29	-31	-37	-31	-11	12	15	19	14

Shaded cells indicate largest reduction in family exposure to that contaminant.

Continuous mechanical ventilation is another intervention that affects all indoor air contaminants, but not always positively. There are different ways to implement this intervention based on climate. For this project, mechanical ventilation was achieved using a continuous exhaust fan. Adding mechanical ventilation using an exhaust fan is the least expensive option, whereas adding outdoor air supply may be more expensive. There is also an incremental cost associated with cooling or heating the added outdoor air. Mechanical ventilation is most beneficial under mild weather conditions, which result in relatively low air change rates due to infiltration.

Mechanical ventilation was most effective in reducing contaminants primarily originating indoors via a continuous source (e.g., CO_2, Rn, and VOC1). Mechanical ventilation also effectively diluted concentrations from contaminants primarily from indoor burst sources (e.g., CO, NO_2, and VOC2). Contaminants originating primarily outdoors were negatively impacted (e.g., particles). The negative impacts of mechanical ventilation tended to be greater than those of the exhaust fan intervention, since the outdoor air intake occurred continuously with mechanical ventilation and only during source events with the exhaust fan intervention. Effective filtration of the incoming air or recirculation air could reduce this impact.

Tightening the building envelope has long been recommended for improving energy efficiency, but the resulting reduction in air change rate can have dramatic effects on pollutants originating indoors. In fact, it was the single worst intervention in terms of increasing the concentrations of CO, CO_2, NO_2, P2, Rn, VOC1, and VOC2. Although it was most effective at reducing P1, P3 and P4, tightening should not be implemented without considering the need for supplementary outdoor air.

Factorial results were also compared across all contaminants by calculating the average percent change in concentration. Based on this analysis, intervention combinations were ranked as shown in Table 12. An ANOVA analysis on these results showed tightening the house to have the most significant impact on contaminant concentrations ($p < 0.001$) followed by using mechanical ventilation ($p < 0.01$) and exhaust fans ($p < 0.01$). Using a more efficient air filter did not have a significant individual impact on the results, but becomes more significant when used in combination with other interventions (see discussion below). Although tightening the house was found to have the most significant impact, it is in the direction of increasing contaminant concentrations. The most effective individual interventions at reducing all contaminant concentrations are the use of mechanical ventilation and exhaust fans.

The combination with the largest decrease across all contaminants was operating exhaust fans, installing mechanical ventilation, and adding a more efficient air filter, without tightening the house. This strategy, however, did have a negative impact on the concentration of P4. The most effective intervention strategy across all contaminants with no negative impacts was operating exhaust fans and adding a more efficient air filter, followed by the installation of mechanical ventilation and a more efficient air filter. Individually, the interventions of exhaust fan and mechanical ventilation led to an overall reduction in contaminant concentrations, but both also led to increased exposures to particles. This result emphasizes the importance of considering combinations of interventions to achieve the most effective strategy. Another intervention combination that has been recommended by ASHRAE 62.2, is tightening the envelope and adding mechanical ventilation that is filtered.[30] For this project, the combination of tightening, mechanical ventilation via exhaust fans, and adding a more efficient air filter resulted in an overall increase in occupant exposure. Thus, tightening the envelope has the potential to overwhelm any additional ventilation, which should be considered when implementing an intervention strategy.

Table 12. Rank of interventions with positive overall impact on average percent change in family exposure.

Rank	Intervention Combination	Average Reduction Over All Contaminants (%)	Negative Impact on Exposure to Contaminants Below:
1	exfan, filter, mv	15	P4
2	exfan, filter	13	
3	filter, mv	9.8	
4	exfan, mv	9.7	P1, P3, P4, P5
5	exfan	7.7	P1, P3, P4, P5
6	exfan, filter, mv, tight	7.4	CO_2, P5, Rn, VOC1, VOC2
7	filter	5.8	
8	mv	4.3	P1, P3, P4, P5
9	exfan, mv, tight	2.0	CO_2, P4, P5, Rn, VOC1, VOC2

exfan: exhaust fan
filter: improved particle filter
mv: mechanical ventilation
tight: envelope tightening

CONCLUSIONS

A factorial simulation method was used to evaluate the effectiveness of different intervention strategies to reduce a family's exposure to indoor air contaminants. In general, intervention combinations that include the use of exhaust fans and mechanical ventilation result in the greatest reduction in contaminant concentrations. Whereas intervention combinations that include tightening tend to increase contaminant concentrations. The most effective intervention combination at reducing the family's exposure to all contaminants was the exhaust fan, mechanical ventilation and the more efficient air filter. If only two interventions can be implemented, then the exhaust fan and more efficient air filter should be used, with the assumption that the HAC system is operating at least 15 % of the time. The more time the HAC system operates, the more effective this intervention combination. If only one of these four interventions could be implemented, the most effective across all contaminants is the exhaust fan during source events, but this single intervention would also have a negative impact on several contaminants. It should be noted that this subset of the overall project did not include any source control interventions. In general, considering the possible large impact on a single contaminant that is possible through source control (e.g., not changing kitty litter indoors), any intervention effort should include a review of sources, particularly large or unusual ones.

The results presented here are specific to this model house, sources, weather conditions, etc. and should not be considered comprehensive or necessarily generally applicable. However, the methodology presented in this paper provides a means to evaluate and compare interventions under a range of circumstances. Future possible studies using this methodology include broadening the scope of the building type and characteristics; including more interventions, contaminants and sources; incorporating an economic analysis of the options; and assigning a ranking of contaminants based on human health effects.

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